High intensity EUV and soft X-ray plasma sources modelling

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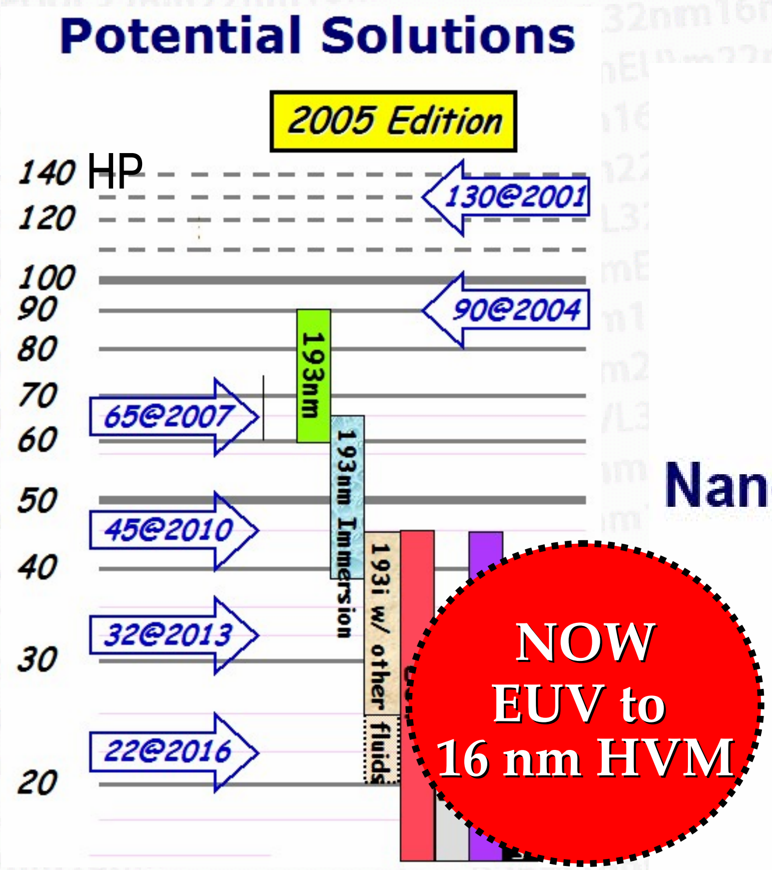
ABSTRACT

The average power of EUV sources at IF required for lithography HVM is higher than presently available. At the same time, for actinic mask blanks, patterned mask and in-situ inspection tools, EUV sources of moderate power but very high brightness are required. In practice, the non-equilibrium plasma dynamics and self-absorption of radiation limits the in-band EUV radiance of the source plasma, and the etendue constraint limits the usable power of a conventional single unit EUV source. Under those conditions one of the primary goals in the development of EUVL is the modelling of plasma-based light sources created by intense lasers and high-current pulsed discharges. A new generation of the computational code Z* is currently developed under international collaboration in the frames of FP7 IAPP project FIRE for modelling of multi-physics phenomena in radiation plasma sources to contribute considerably to solving current EUVL source problems as well as extending their application to subsequent nodes (16nm and beyond) and to shorter wavelength radiation applications. The radiation plasma dynamics, the spectral effects of self-absorption in LPP and DPP and resulting conversion efficiencies are discussed. The modelling results are guiding a new generation of multiplexed sources being developed at NANO-UV, based on spatial/temporal multiplexing of individual high brightness units, to deliver the requisite brightness and power for lithography, actinic metrology and soft X-ray imaging applications.

EUV Lithography

chosen for nano features microchip production



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EUV source for HVM & actinic mask inspection
- a key challenge facing the industry

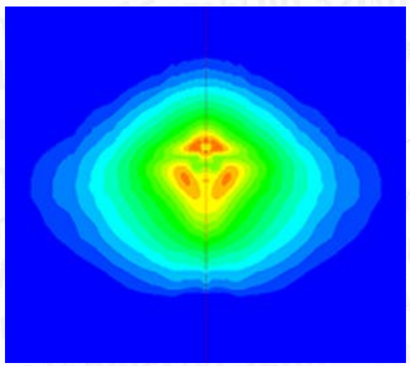
EUV Light Source

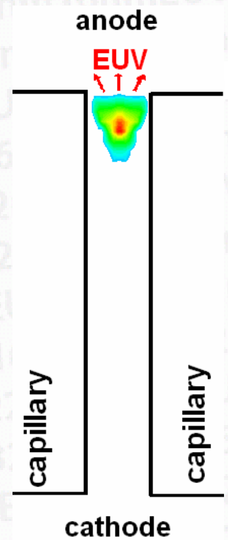
- Sn, Xe, Li … high energy density plasma (T_e=20-40eV) - EUV light source in narrow 2% band around 13.5nm wavelength
- LPP & DPP - methods to produce the the right conditions for HED plasma

LPP

combined NdYAG +CO_2

$I = 10^{11}$ W/cm^2
T_e = 40eV
N_e =10^{19}-10^{21} cm^{-3}





DPP

micro plasma

j = 1 - 10 MA/cm^2
T_e = 20-30eV
N_e =10^{15}-10^{17} cm^{-3}

Z * MHD code modeling

- For HVM - 200-500 W of in-band power @ IF with etendue < 3mm^{2}sr
- For mask inspections ABI→AIMS→APMI – 10 →100 →1000 W/mm^2·sr at-wavelength radiance

- kW (source) ⇒ W (IF) is the source of the problem -

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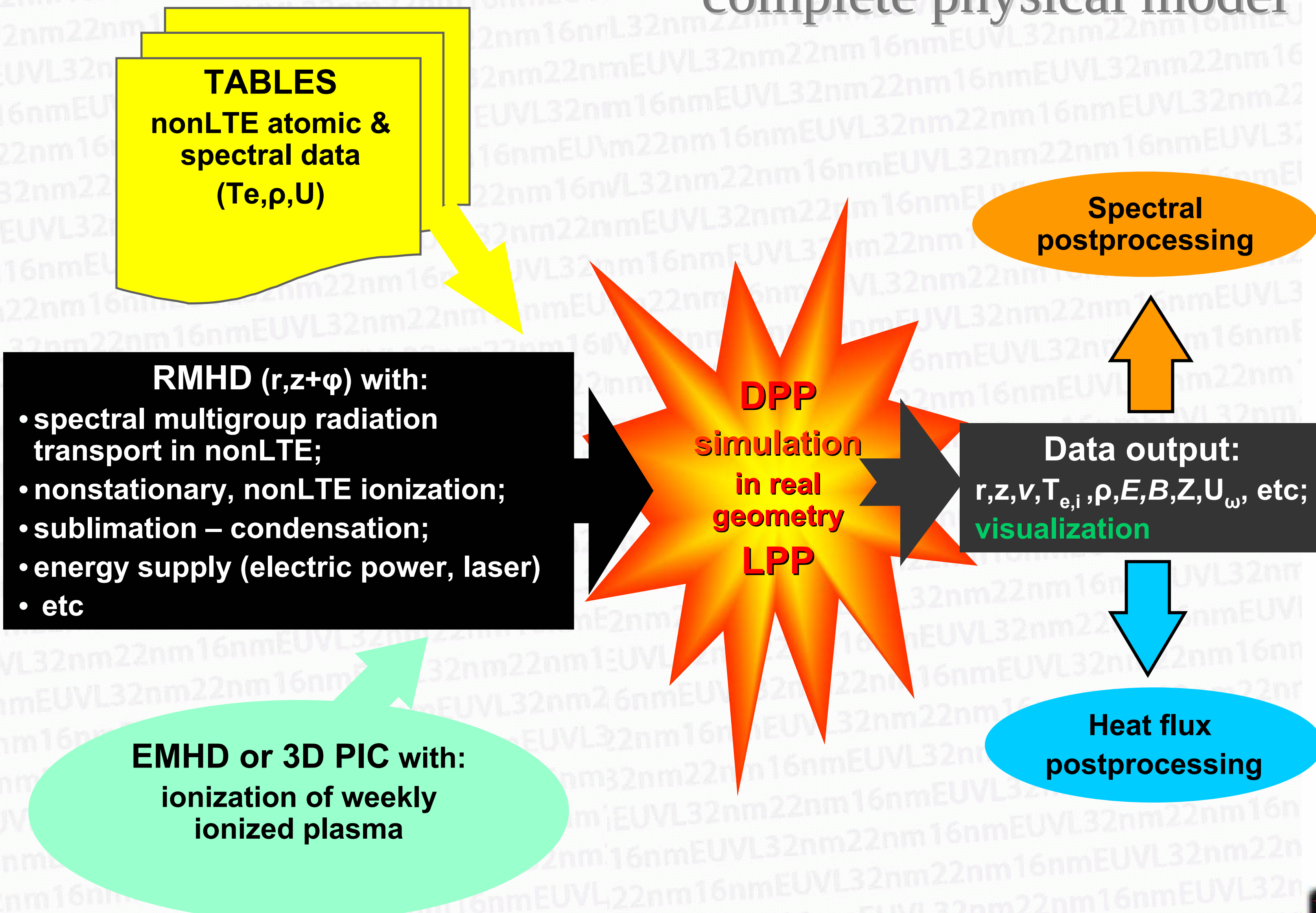
Next Generation Modelling Tools
- FP7 IAPP project FIRE

- Theoretical models and robust modeling tools are developed under international collaboration in the frames of European FP7 IAPP project FIRE
- The FIRE project aims to substantially redevelop the Z* code to include improved atomic physics models and full 3-D plasma simulation of
  - ✓ plasma dynamics
  - ✓ spectral radiation transport
  - ✓ non-equilibrium atomic kinetics with fast electrons
  - ✓ transport of fast ions/electrons
  - ✓ condensation, nucleation and transport nanosize particles.
- Modelling can be the key factor to scientific and technological solutions in EUVL source optimization with fast particles and debris to solve current EUVL source problems as well as extending their application to 22nm and beyond.
- The research and transfer of knowledge is focused on two major modeling applications;
  - ✓ EUV source optimization for lithography and
  - ✓ nanoparticle production for nanotechnology.
- Theoretical modelling will be benchmarked by LPP and DPP experiments

ZETA → Z* RMHD Code → Z* BME

complete physical model



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EUV Brightness Limit of a Source

- The intensity upper Planckian limit of a single spherical optically thick plasma source in $\Delta\lambda/\lambda$=2% band around λ=13.5nm

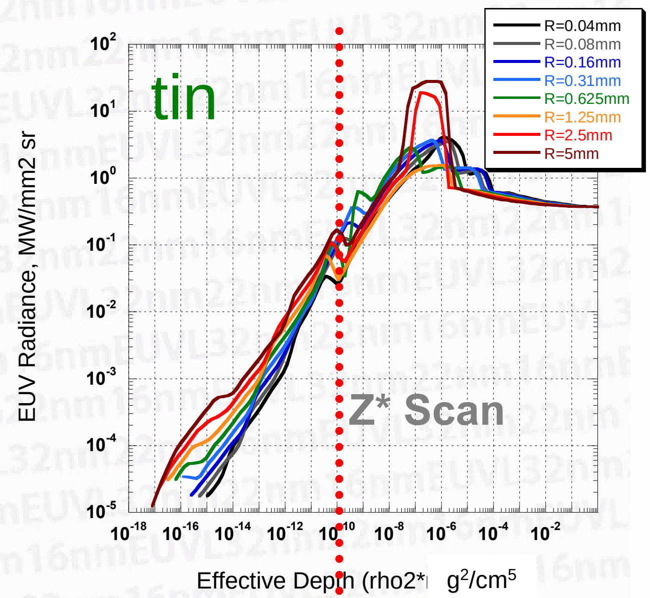
$$I = \frac{2hc^2}{\lambda^4}\frac{\Delta\lambda/\lambda}{e^{\frac{hc}{\lambda T}}-1} \approx \frac{72}{e^{\frac{92}{T(eV)}}-1}(MW/mm^2 sr)$$

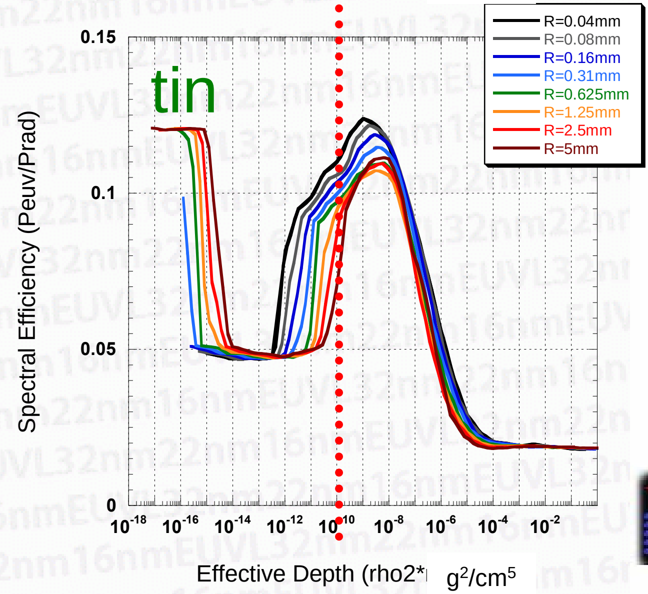
- Source with pulse duration τ and repetition rate f yields the time-average radiance $L = I\cdot(\tau f)$

- At $T\approx 22eV$ $L \approx 1.1(W/mm^2\ sr)\cdot\tau(ns)\cdot f(kHz)$

- Plasma self-absorption defines the limiting brightness of a single EUV source and required radiance
- The plasma parameters where EUV radiance is a maximum are not the same as that when the spectral efficiency is a maximum.

- the Conversion Efficiency of a single source decreases if the in-band EUV output increases (at the same operation frequency)





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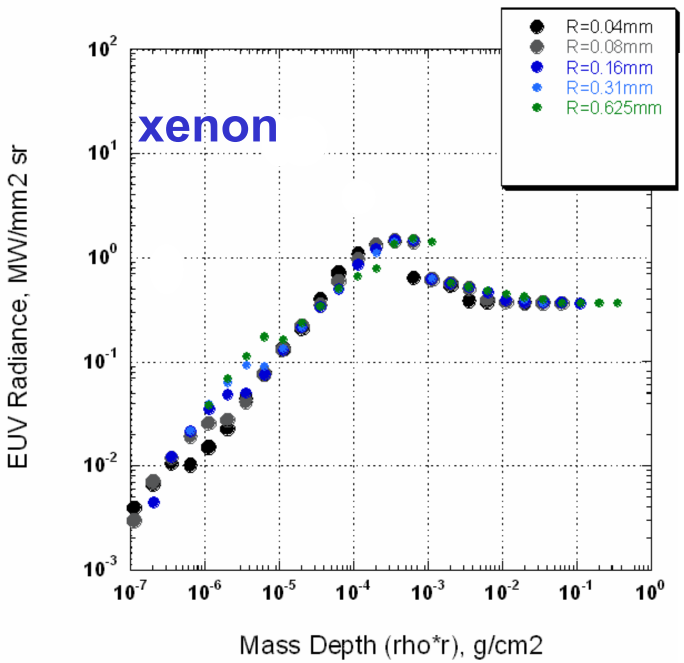
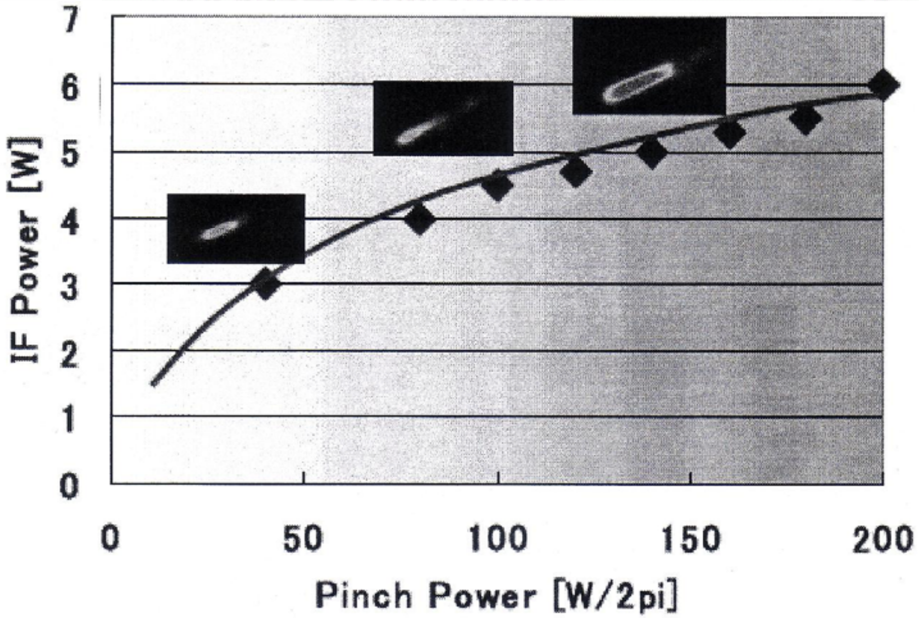
EUV IF Power Limitation:
prediction vs. observation

- Low temperature Xenon plasma EUV emission



Xenon plasma parameter scan with Z*-code showing the in-band radiance limitation from XeI-XeXI ions



Experimental observation of limitation of the in-band EUV power at IF from xenon DPP source

[M. Yoshioka et al. Alternative Litho. Tech. Proc. of SPIE, vol. 7271 727109-1 (2009)]

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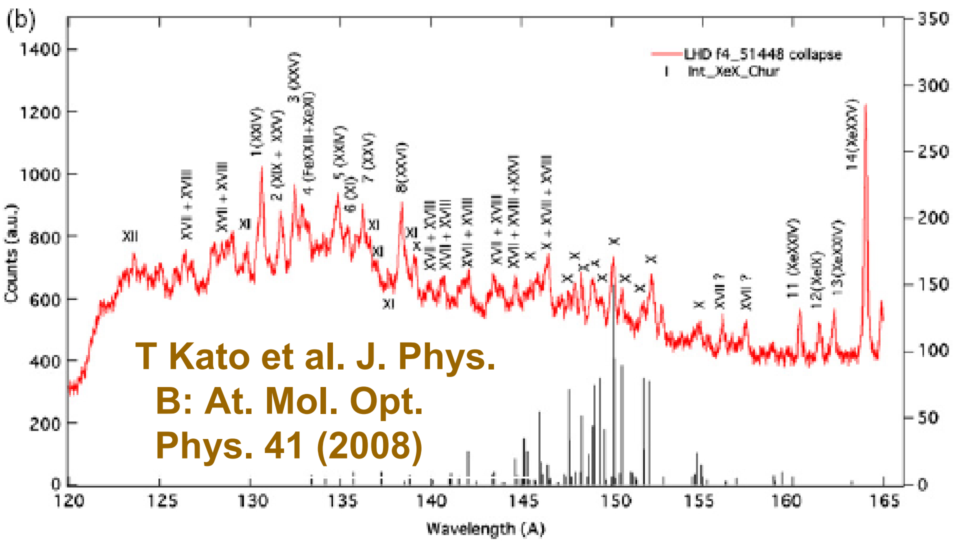
Bright EUV Emission

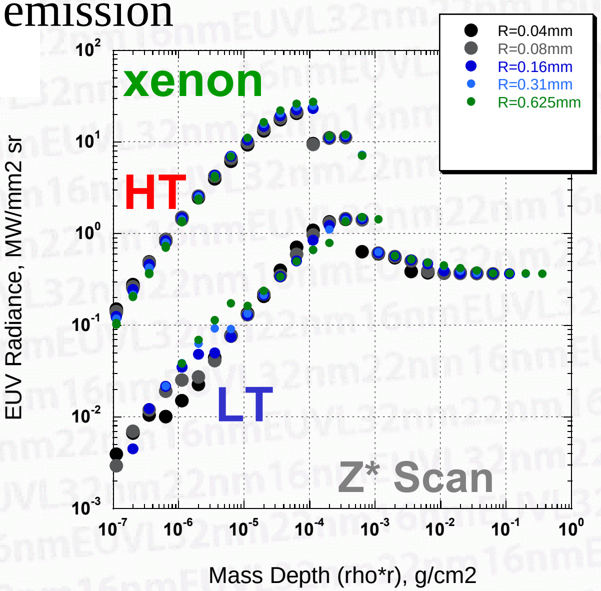
from highly charged xenon ions

Tokamak experimental data



T Kato et al. J. Phys. B: At. Mol. Opt. Phys. 41 (2008)

- There are two regimes in transparent plasma of xenon: Low - Temperature (LT) with XeXI and High - Temperature (HT) with XeXVII-XeXXX ions contributing into 2% bandwidth at 13.5nm.
- For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission



- **XeXXII - XeXXX** produce bright 4f-4d*, 4d-4p*, 5p-4d* [White, O'Sulivan] ($3d^n4f^1 + 3d^n4p^1 \rightarrow 3d^n4d^1$) satellites in EUV range near 13.5nm
- **XeXXII** has ionization potential 619eV

(for more details see poster: Vasily S. Zakharov et al)

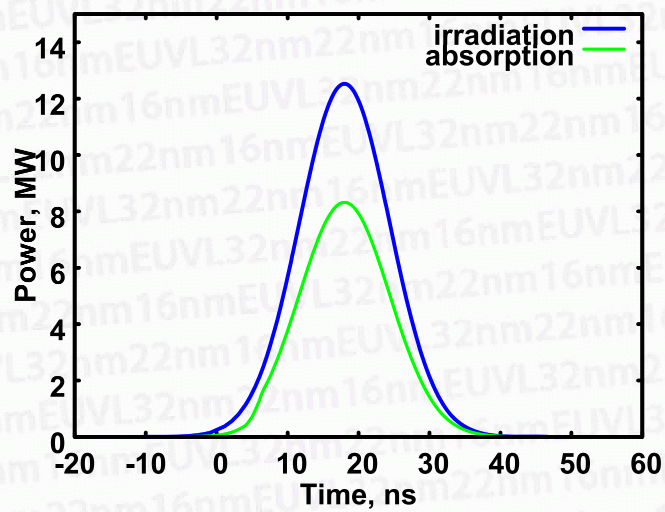
LPP Dynamics

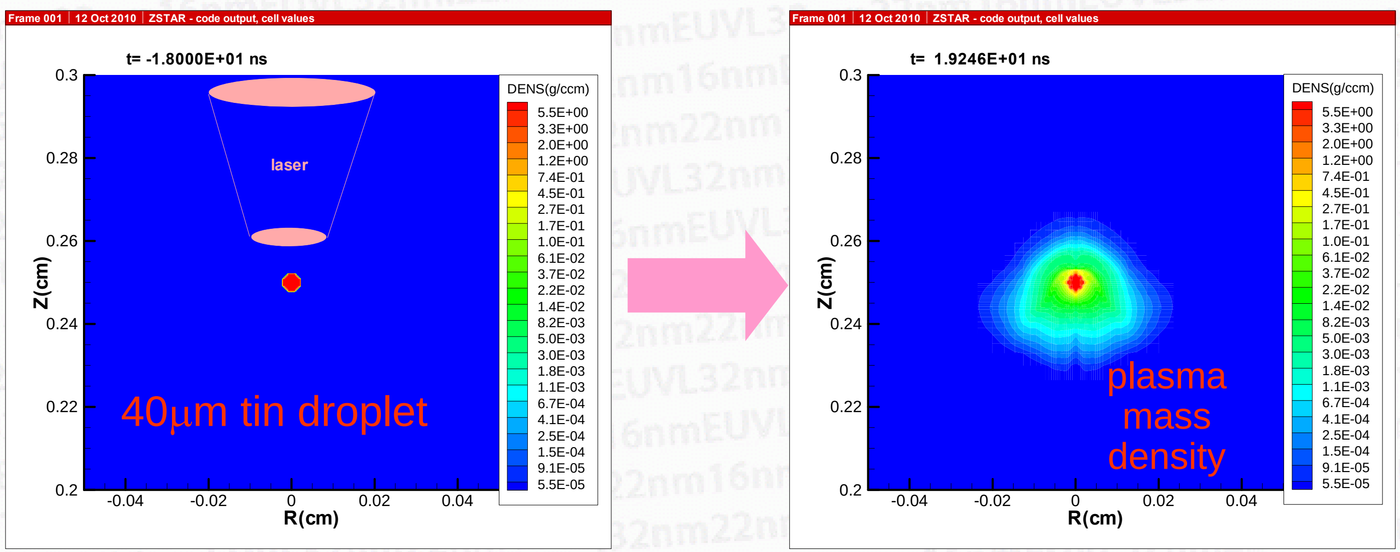
under CO_2- laser pulse

CO_2-laser pulse:

Pulse energy	200mJ
Pulse duration	15ns FWHM
Focal spot size	200 µm

Loses: reflections and large focal size at initial moment





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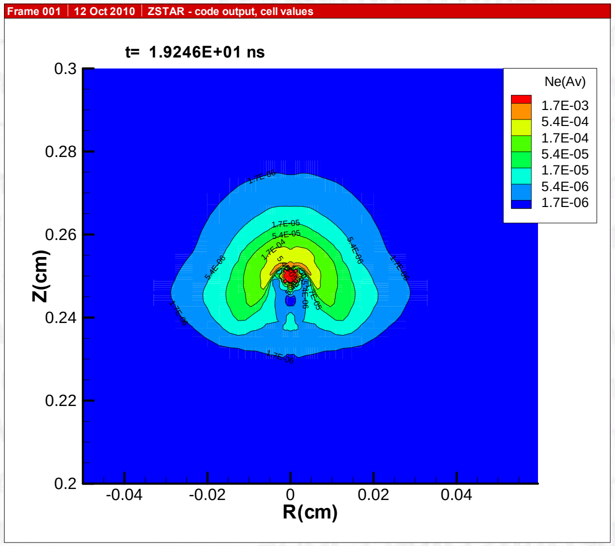
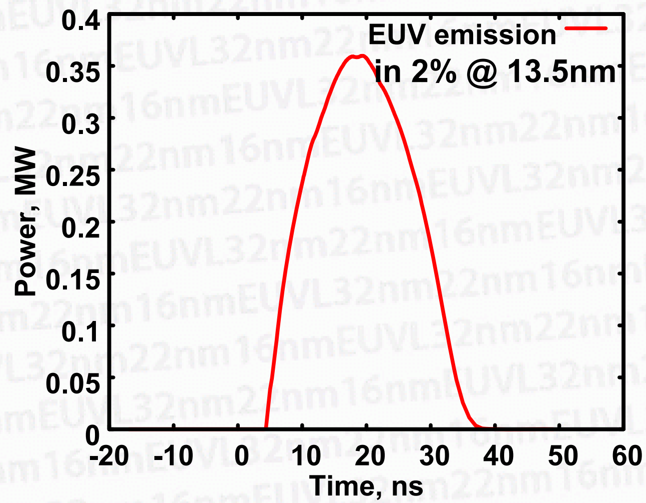
EUV Emission

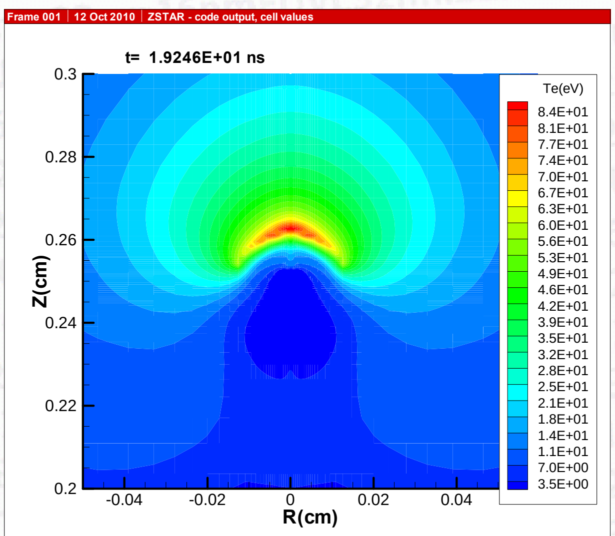
under CO_2- laser pulse

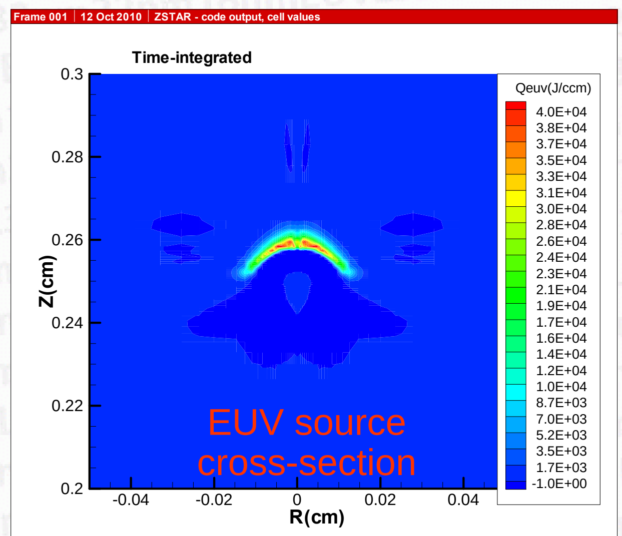
plasma electron density N_e





plasma electron temperature T_e





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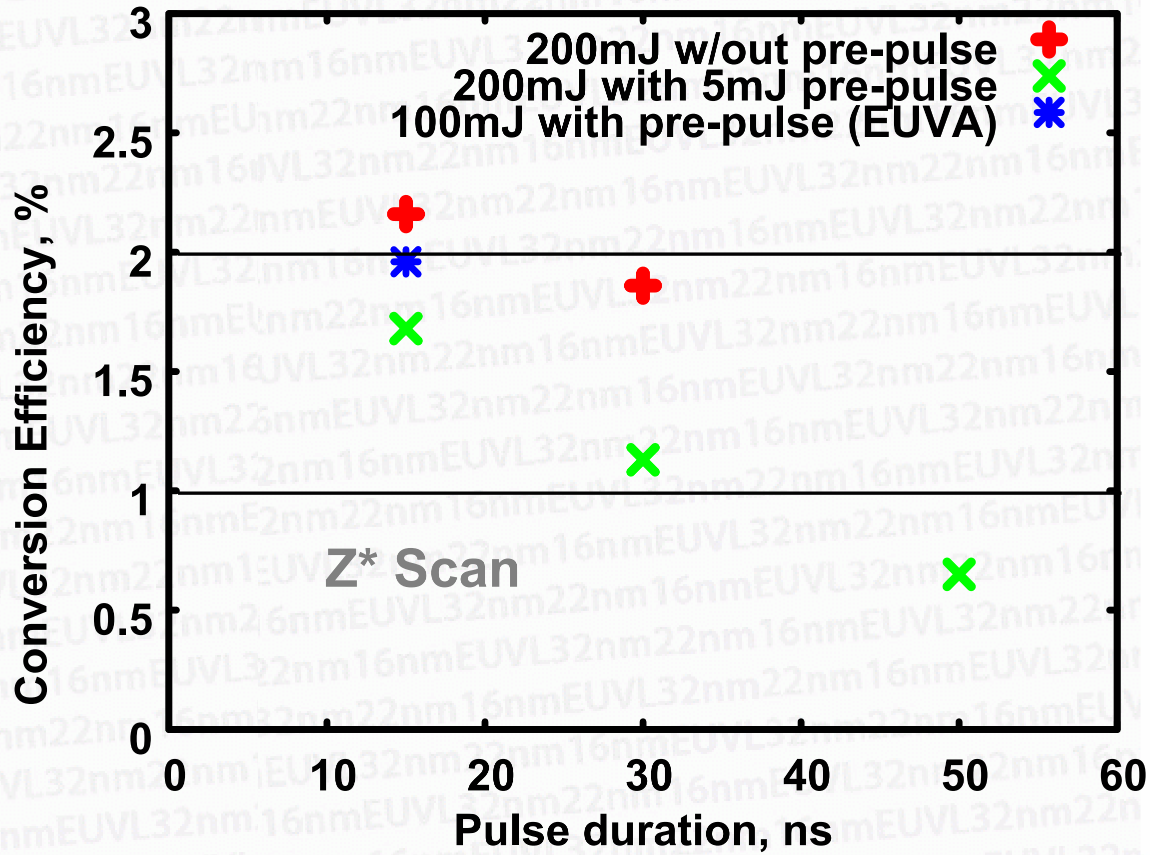
Conversion Efficiency of CO_2-laser
on pulse duration, with & w/out pre-pulse

Main pulse: CO_2-laser 0.2 J/pulse, 15, 30 and 50ns fwhm, 200μm focal spot size
Pre-pulse laser (if applied): Nd:YAG 5 mJ/pulse, 10ns fwhm, 40μm spot size

Target:
40μm diameter
tin droplet
(20 μm for
100mJ laser)



Calculated EUV brightness is up to 24 W/mm² sr kHz

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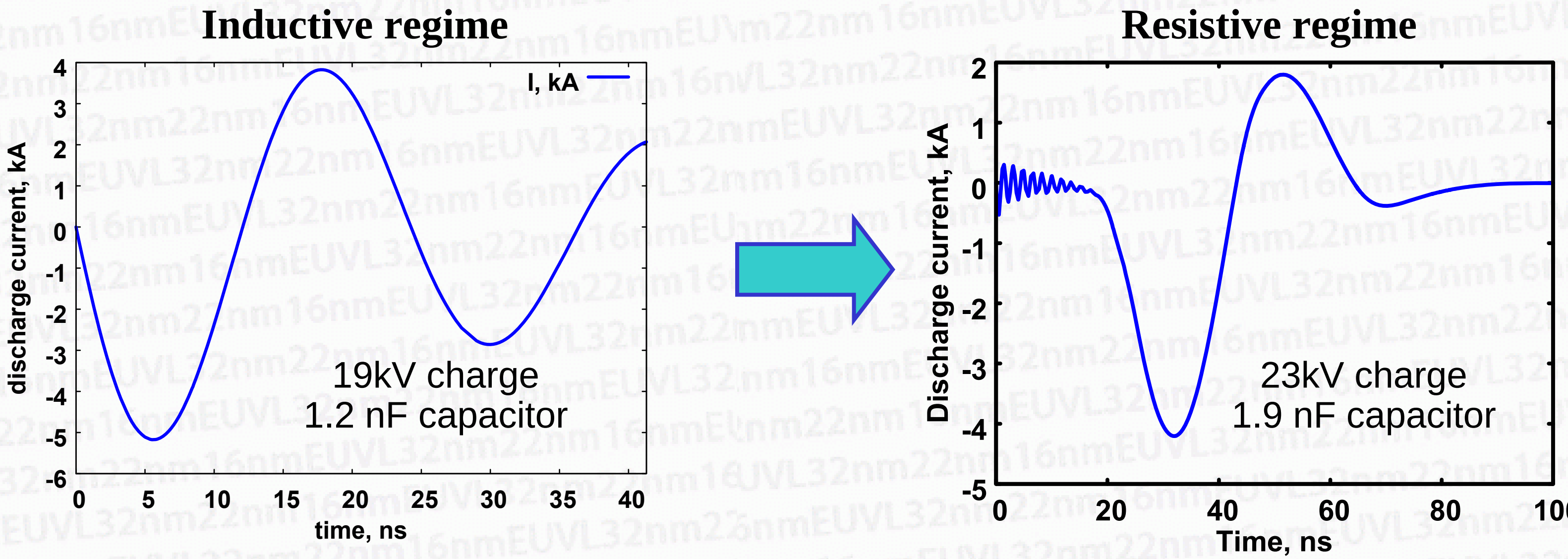
Capillary Discharge EUV Source

resistive regime

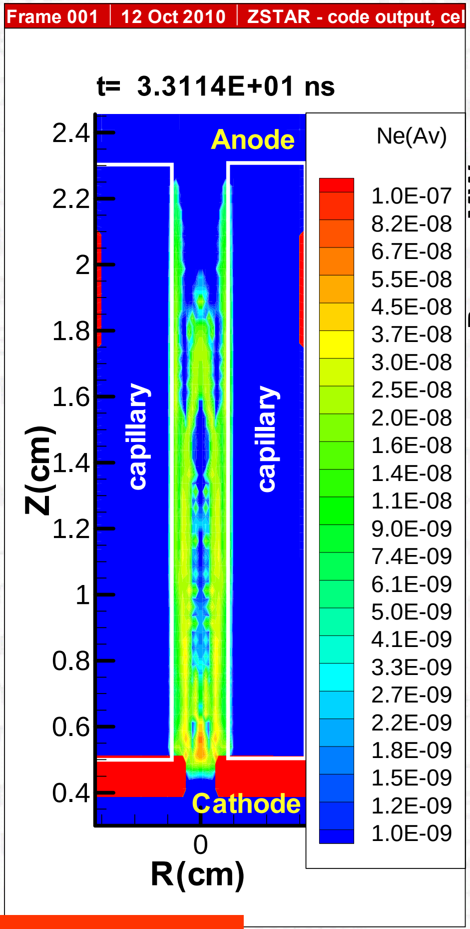


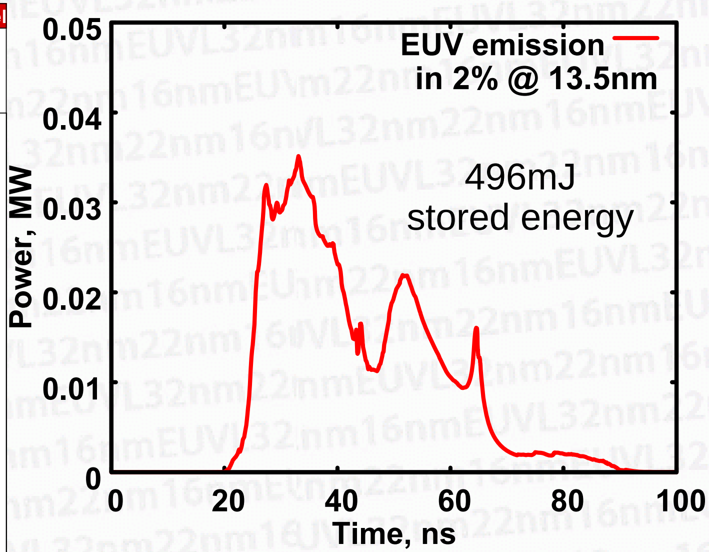
In a resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission consequently.

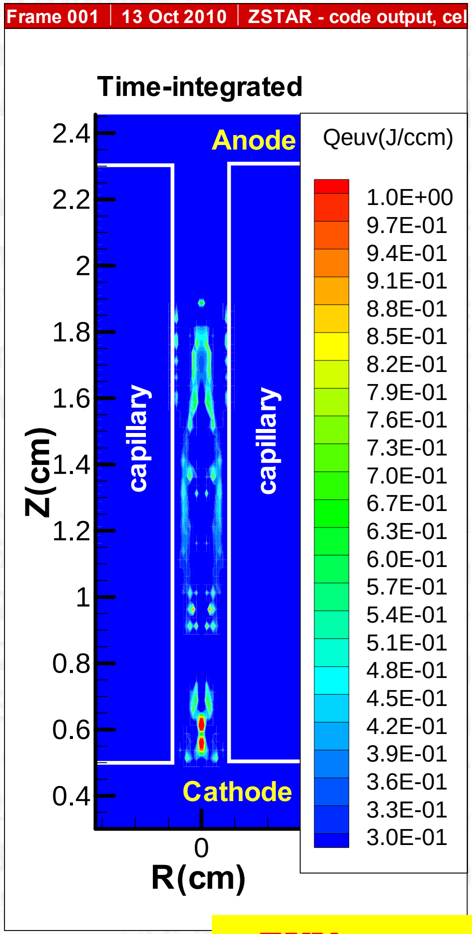
Also, fast electrons increase the ionization degree of heavy ion (Xe,…) plasma increasing eo ipso EUV yield.

Capillary Discharge EUV Source

dynamics & EUV emission







At EUV emission maximum:
N_e=2-3 $\cdot 10^{16}$cm^{-3},
T_e=25-40eV.

3D volumetric compression

Calculated EUV brightness is up to 10 W/mm² sr kHz

EUV source cross-section

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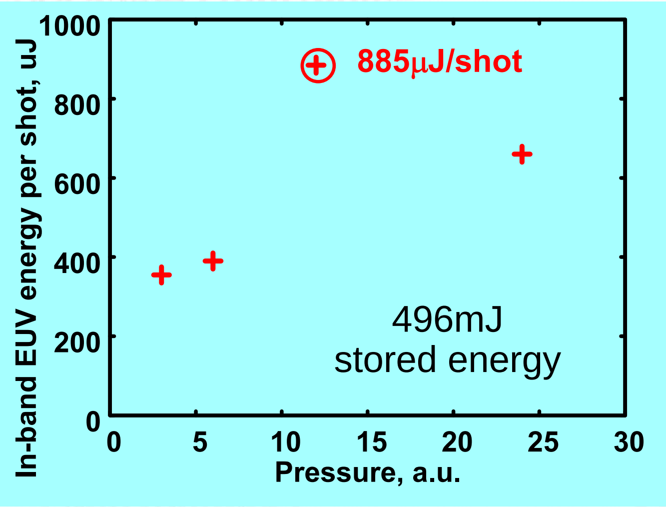
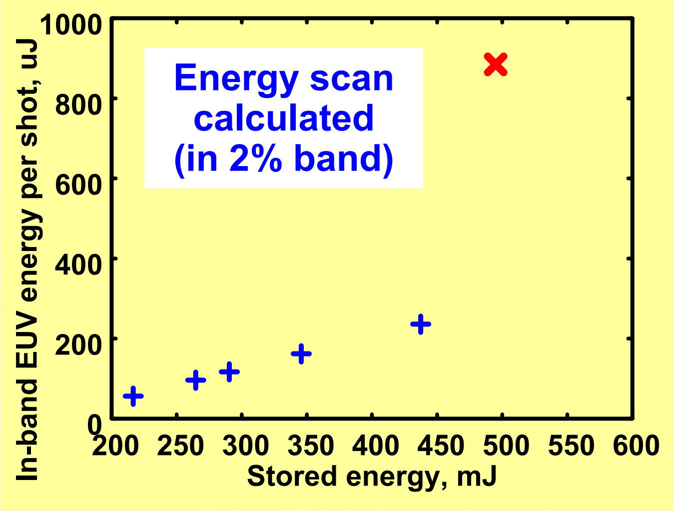
Gen II EUV Source
- characteristics & optimization from Z* modelling



Optimization
by gas mixture
pressure

EUV source
scan by stored
electrical energy



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Multiplexing

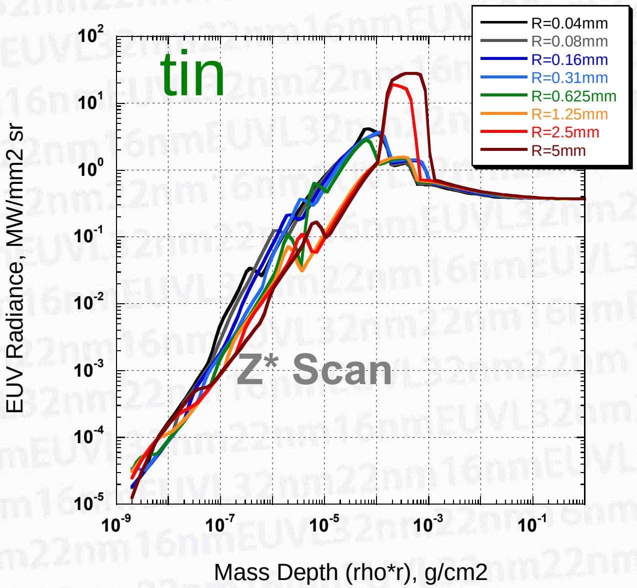
- a solution for high power & brightness

- Small size sources, with low enough etendue $E_1 = A_s \Omega << 1\ mm^2\ sr$ can be multiplexed.
- The EUV power of multiplexed N sources is

$$P_{EUV} \propto \sqrt{E \cdot N \cdot \Omega} \cdot \tau \cdot f$$

$\Rightarrow$ The EUV source power meeting the etendue requirements increases as $N^{1/2}$

- This allows efficient re-packing of radiators from 1 into *N* separate smaller volumes without losses in EUV power

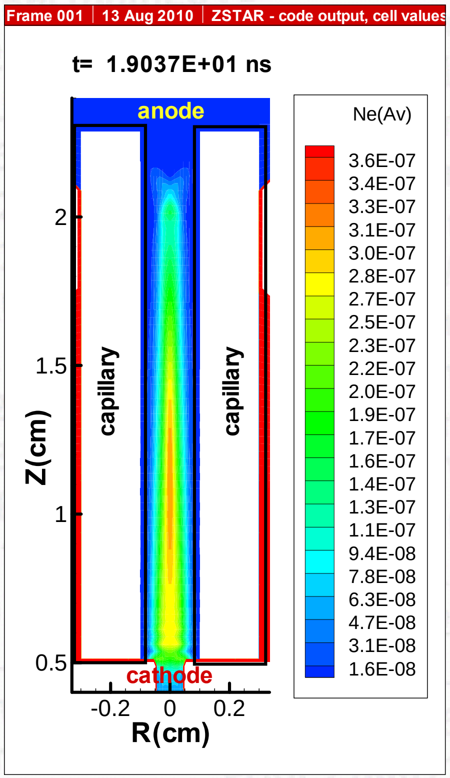


- **Spatial-temporal multiplexing:** The average brightness of a source and output power can be increased by means of spatial-temporal multiplexing with active optics system, totallizing sequentially the EUV outputs from multiple sources in the same beam direction without extension of the etendue or collection solid angle

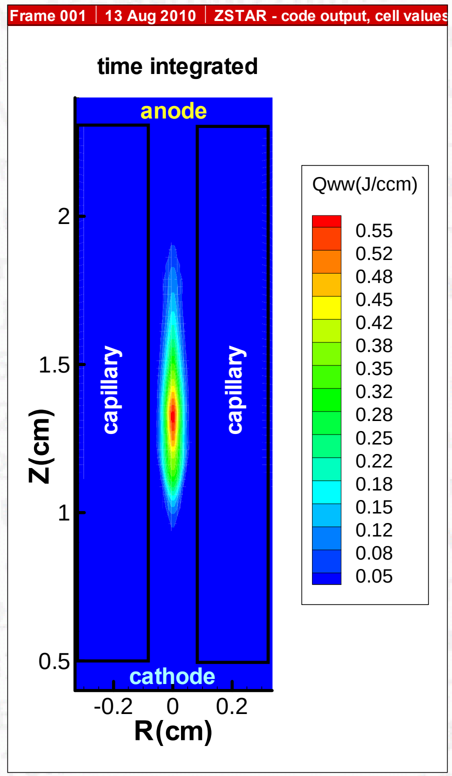
MPP source for soft x-ray microscopy

Z*-code modelling

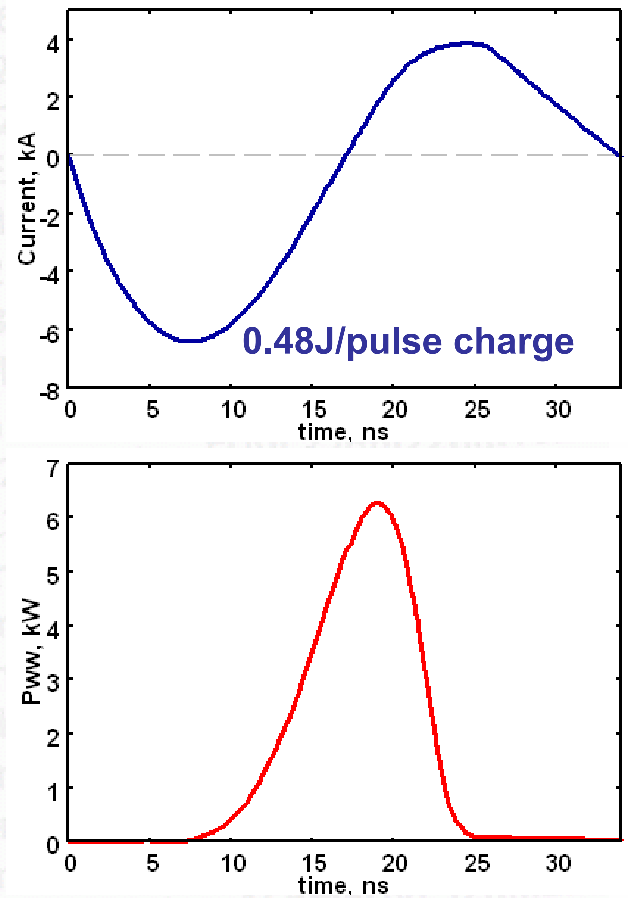
Nitrogen plasma at emission maximum



Time integrated image of soft x-ray (400 - 600eV) source



Discharge current and soft x-ray pulse



0.48J/pulse charge

Fast electrons induced discharge in 3-D volumetric compression regime

<Z> ≈ 5

T_e = 45 - 55eV

$N_e \approx 2\cdot10^{17} cm^{-3}$

Nitrogen: He-like and H-like

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